5th Ka-Band

A Ka-band High Data Rate Shipboard Satellite Terminal

Michael A. Rupar
U.S. Naval Research Laboratory, Code 5554
4555 Overlook Ave. SW, Washington, DC 20375
(202) 767-3155, fax (202) 767-3377
rupar@itd.nrl.navy.mil

David R. Beering, David E. Brooks
Infinite Global Infrastructures, LLC
At NASA Glenn Research Center
(630) 665-1396, fax (630) 665-1297
drbeering@sprynet.com, dbrooks@obelisk.org

Douglas J. Hoder
NASA Glenn Research Center
21000 Brookpark Road, Cleveland, OH 44135
(216) 433-3438, fax (216) 433--6371
dhoder@grc.nasa.gov

1. Abstract

A fully articulated steerable shipboard satellite antenna system operating at Ka-band was developed by engineers from the Naval Research Laboratory (NRL), NASA's Glenn Research Center, and a number of industry partners. A series of tests conducted in October of 1998 on Lake Michigan achieved an unparalleled data rate transmission of 45 megabits per second (Mbps) between a moving vessel at sea and a fixed-earth station using NASA's Advanced Communications Technology Satellite (ACTS). Network and application layer tests ran concurrently with the data rate transmission trials, examining TCP/IP file transfers, video and voice transfer technologies, and Asynchronous Transfer Mode (ATM) techniques.

This experiment, called the Shipboard ACTS Ka-band Experiment (SHAKE), collected a data set of time-correlated measurements. The samples, collected at one-second (or faster) intervals, included vessel motion, RF and IF (modem) measurements, DS-3 layer port statistics, ATM layer statistics, TCP/IP statistics, and application performance. This data set (discussed herein) represents the one of the most comprehensive collections of its type ever recorded on a vessel. Tracking was measured at various sea states and weather conditions, including seas that generated peak pitch variations on the vessel of $\pm$ 12°, and peak roll variations of $\pm$ 24°.

The SHAKE experiment, utilizing a combination of commercial-off-the-shelf (COTS) and government hardware, clearly illustrated the viability of high data rate (HDR) Ka-band systems for ship-to-shore communications. The system, which was developed over a period of four months, was tested during a two-week period on Lake Michigan on a 45-foot Bayliner Motor Yacht, *Entropy*.

Underlying networking, protocol, terminal, and bandwidth-on-demand issues, combined with variable bit rate service and HDR capabilities, present challenges not typically addressed in current Naval SATCOM systems. Through this study, numerous system optimizations were documented, which are presented as work remaining in order to realize reliable services that would support Naval HDR shipboard SATCOM requirements using commercially-available Ka-Band satellite systems.

2. Introduction

NASA's Advanced Communications Technology Satellite (ACTS) was launched in September of 1993 to accelerate the advancement of satellite communications systems. ACTS operates in a geostationary orbit at 100°W Longitude. The NASA Glenn Research Center (GRC) in Cleveland, OH manages the satellite and its associated ground systems. System attributes once considered unique to ACTS are now becoming common in modern satellite systems, including the use of high-gain spot beams, a high-gain steerable antenna, and a family of high data rate, very small aperture terminals.

Using current technology, the Navy cannot link HDR shipboard local area networks (LANs) to terrestrial networks at comparable speeds while ships are away from port. This problem is exacerbated on the smaller deck combatants, where there is not a large amount of space for the installation of a satellite antenna system and associated below decks electronics. Recent evolution of the Global Broadcast System (GBS) into Ka-band service has enabled a one-way HDR channel from a hub out to the fleet. By transitioning to Ka-band, with transmit and receive frequencies at approximately 30 and 20 GHz, respectively, the aperture size necessary for a communication link is reduced substantially compared to existing systems. For example, the performance of a 2.4m parabolic reflector antenna at C-band is comparable to a 0.5m antenna at Ka-band.

The Satellite and Wireless Technology Section (Code 5554) at NRL has been tasked to develop and demonstrate techniques to enable HDR WAN satellite and wireless connectivity from ships. HDR satellite communications is a critical component of many of these programs. NRL teamed with engineers at NASA GRC to explore the opportunities for shipboard communications in Ka-band. The goal was to create an experiment that would demonstrate both the feasibility of a HDR full-duplex satellite link between a shipboard platform and a shore installation, and to take quantitative and qualitative measurements of the shipboard terminal performance.

To date, several mobile experiments (e.g. [1]-[2]) have been performed with ACTS, using a variety of different terminals supporting data rates ranging from 10 kilobits per second up to two megabits per second. These experiments have been performed on a variety of vehicles such as aircraft, land mobile vehicles, a commercial seismic acquisition vessel, and a US Naval vessel (an Aegis cruiser). The highest ship-to-shore satellite data rate demonstrated during these experiments was a link operating at two megabits per second between the MV Geco *Diamond* and NASA's Jet Propulsion Laboratory, using JPL's slotted waveguide mobile antenna system [3]. This experiment was performed in conjunction with the American Petroleum Institute's ATM Research & Industrial Enterprise Study (ARIES) project in February of 1995.

To enable such a great leap in performance (without a significant expense to the government), NRL and NASA enlisted the participation of a number of leaders in the fields of satellite technology and HDR networking. Infinite Global Infrastructures, of Chicago, IL, was a partner in the system and testbed development. The satellite terminal was assembled using a 1.0m antenna system provided by SeaTel, Inc., of Concord, CA. Sea-Tel was a member of the development team and provided on-site support and assistance. Hill Mechanical Group provided the test vessel, designed and built the antenna mounting structure and provided a base of operations and assistance in Chicago. Equipment was also provided by FORE

Systems, of Pittsburgh, PA; Xicom Technologies, Santa Clara, CA; Raytheon Marine Company, Manchester, NH; and Comsat Laboratories, Clarksburg, MD.

3. Experimentation

Tests establishing a two-way, 45 Mbps ATM link between the ship and the fixed station (hub) at GRC in Cleveland, OH, were conducted off the coast of Chicago, IL, on Lake Michigan onboard the Bayliner during the period of October 9-23, 1998, using the ACTS spacecraft. A picture of the vessel underway is shown in Figure 1.

The hub was an existing ACTS HDR station equipped with a NASA-developed custom Up/Downconverter and an EF Data SDM-9000 satellite modem with a DS-3 interface. The satellite link was optimized by the use of a COMSAT ALE-2000 ATM Link Enhancer (ALE) using a adaptable coding rate. ATM Cell-Level Reed-Solomon Forward Error Correction, located between the modem and a FORE Systems ASX-200BX ATM switch. Connected to the ATM switch was a Sun Ultra1 workstation, along with ATM video and audio adapters, which were also provided by FORE Systems.

The 1.0m SeaTel shipboard terminal was originally configured for operation at Ku-Band. This antenna system was integrated for Ka-band operation by a team of engineers and technicians from SeaTel, NASA and NRL, incorporating hardware contributions by all three organizations. The terminal included a NASA-designed primary Up/Downconverter, conscan tracking, a Xicom 120W Ka-band power amplifier, and the same modems as used at the hub. Terminal heading stabilization was attained by a precision gyro compass made by the Raytheon Marine Company.

The end-to-end communications system from the vessel to the hub supported the transmission and reception of high-speed TCP/IP data transfers, interactive TCP/IP data, production-quality video, and CD-quality audio. A block diagram of the test configuration is provided in Figure 2.

Ship pedestal performance was measured at a number of points in the system. Ship motion was recorded on the bridge (pitch, roll, yaw, linear acceleration), received signal level (downconverted to IF) was measured at the receiver, and modem data performance parameters (bit energy-to-noise ratio, or Eb/No, Raw BER, Corrected BER and carrier detect) were recorded as well. An example of ship motion and the corresponding SHAKE RF and network system performance is given later in this paper. A more thorough discussion on the SHAKE program and its results can be found in [4,5].

Network performance statistics were gathered at multiple locations within the data network to study the impact of physical link errors to the recovery of a data mover application transferring data between the hub and ship workstations. These measurements were taken at one-second intervals, and were conducted at the same time as the RF measurements. The test applications used TCP/IP protocols to guarantee the integrity of data. The TCP/IP protocol operates by re-transmitting lost data and decreasing the application's utilization of the link by throttling back during periods of link congestion, or physical link errors caused by low Eb/No, loss of tracking, or bit errors affecting the network payload framing and PDUs at the DS3 and ATM layer.

Among the diagnostics taken were an extensive number of ATM switch statistics, which are detailed below. Other diagnostics, such as TCPdump (an upper-level analysis tool that looks at TCP's behavior using TCP-based applications and Unix host interface (Netstat) statistics, were rather extensive and technically detailed in nature, and are not within the scope of this paper.

ATM Switch DS-3 Port Statistics

The ATM network interfaced to the EF Data modem at a DS-3 rate (44.736 Megabits per second). The switch port maintained a multitude of DS-3 performance parameters and alarms that were available for polling by a network management program. A port statistics program was written in C to automatically poll the switch port once each second. This program used the TCP/IP protocol to talk to the switch, and Simple Network Management Protocol (SNMP) to poll the interface statistics. Among the more relevant of some twenty interface parameters were:

- DS-3 Framing errors
- DS-3 Bit errors
- Count of Valid ATM Cells transmitted and received
- Count of discarded ATM cells
- Link synchronization errors
- ATM Physical Layer Convergence Protocol Errors

The two modems provided DS3 framing for the ATM switches to create an ATM network over the satellite link. The two workstations used TCP/IP over ATM to support all applications, including e-mail, WWW, and the data mover application. Any errors recorded on the DS3 interface of either ATM switch, such as ds3AtmHCSs and ds3FramingPbitPERRs generally indicated RF problems caused by the modem and/or RF link.

III. RESULTS

A. Tracking Performance

It was noted that the tracking performance of the pedestal appeared to be detrimentally affected by a) the limitations of the gyrocompass to track heading, and b) linear acceleration by the vessel. In sea states with great variations in pitch and roll, the pedestal often maintained not only track of the satellite downlink, but also a good signal-to-noise ratio and consistent performance of the ATM switches at each end of the link.

While the gyrocompass was quite accurate, it exhibited a tracking limitation of approximately 5°/second. When turns were made at rates higher than that limitation, the terminal was often unable to maintain track of the satellite, and the signal level disappeared entirely. The terminal would automatically reacquire the signal once the rapid turning ceased, usually within one minute.

Terminal tracking performance was often compromised during vessel acceleration, especially when the heading was directly towards or away from the azimuth look angle to the satellite. It is believed that this was because of the large weight of the power amplifier (PA) and corresponding counterweight mounted on the pedestal with the antenna. To get maximum power to the antenna, both the primary Up/Downconverter and the PA were mounted behind the reflector on the pedestal. The entire assembly was balanced so that the antenna could be maneuvered with minimal motor control. However, during ship acceleration, the antenna assembly was believed to lag the motion of the base of the terminal, creating a rearward motion of the reflector and breaking the track of the satellite. This track loss was not observed to the same extent during deceleration.

The tracking performance is shown in Figures 3 and 4 for a non-ideal case, when due to extreme ship motion in run #38 (taken on 10/20/98), the terminal lost lock completely. The point at which lock was lost can be found in Figure 4, when the roll rate surged to nearly $\pm$ 25 degrees/second, more than double the specifications for the pedestal.

B. Physical and Network Layer Performance

Experiments in transferring data via ACTS from a workstation disk drive on the Entropy to another workstation (or a tape drive) at GRC achieved maximum sustained single stream user data rates of 40.5 Mbps. The commercial Internet was also accessed via ACTS through GRC to NRL and other sites on the web. The application experiments conducted concurrently with the transmission trials included:

- TCP/IP file transfers simulating the high-speed transfer of imagery, such as strategic and tactical theater information, to and from the vessel. This data transfer technique is also applicable to a host of near-Earth orbit NASA spacecraft that routinely transmit data from space to ground using geostationary relay satellites. Data transfer tests were conducted in disk-to-disk, disk-to-tape, and tape-to-disk configuration. The tape device was a DIS-160 high-performance tape subsystem, provided by Ampex Data Systems.

- Multiple independent web-based data streams were sent from a server at GRC to the vessel, each operating at 500 kbps. These transfers were typically invoked at 30 second intervals and involved files on the order of several megabytes. Performance was in the 300-400 kbps range per transfer, with a maximum of ten transfers running simultaneously.

- Technologies for real-time video and voice delivery. These technologies can be used for video conferencing, crisis response, telemedicine, mentoring, distance learning, and entertainment. The video encoding technology used was Motion JPEG, running at 17 Mbps in both directions over ATM. This was operating concurrently with the other experimentation except for the HDR (40 Mbps) data transfers. The CD-quality audio was embedded within the video data stream.

Figure 5 shows the received signal strength (measured at IF of 70 MHz) and the Eb/No (measured by the modem) during another portion of run #38, where the terminal lost synchronization, but then recovered. It is interesting to note that the modem had some difficulty in maintaining sync once the link had recovered, taking approximately two minutes before "settling" in.

The ATM and RF layer statistics illustrate how the network recovered as the RF link repaired itself, followed by the ATM layer and finally the TCP/IP application recovery to a full rate transfer. Figure 6 illustrates the correlation between HCS (header check sum) errors and modem Eb/No for the same dropout/recovery period in run #38. Figure 7 shows the received traffic from shore along with the corresponding (corrected) BER recorded at the modem. Some instances of traffic flow immediately after a dropout may due to the 1 Hz recording rate of the data (at 1 Hz).

ATM layer performance was excellent when the link maintained an Eb/No of 5.8 dB or better. Reed-Solomon encoding/decoding (RS) was employed at the modems for a majority of the testing (with the remainder relying on the variable code rate RS at the ATM Link Enhancers by turning off the R/S in the modem.), with the result that when the Eb/No dropped to 5 dB or lower, the link went down completely. The ALE allowed the link to close at a lower Eb/No than using the fixed code rate. This was at the expense of full DS3 data for the user.

V. CONCLUSIONS

The NRL-NASA Shipboard ACTS Ka-band Experiment (SHAKE) provided a significantly greater data rate than the current Navy shipboard standard, demonstrating data rates of 45 Mbps and user application (file transfers, video teleconference) data rates of above 40 Mbps, significantly higher than the current 1.5 Mbps or 64 kbps standards. While future Navy systems may not require 45 Mbps to a single platform, it is likely data rates in the 1-2 Mbps range, with the ability to increase as required, will be required on a larger number of ships and combatants than is currently available.

SHAKE demonstrated the capability that exists in the commercial world (albeit not entirely "off-the-shelf") to meet the future needs of HDR satellite networking at sea. The experiment also identified a number of developments that are still necessary before such a system is ready for operational deployment, such as improved radomes and primary reflectors for Ka-band, lighter weight power amplifiers, rotary joint dependability, and the need for more sophisticated tracking algorithms. ATM proved to be a worthy technology in providing mixed-media support and rapid reconfiguration required for a dynamic shipboard environment. Additional benefits to the Navy for shipboard ATM deployment include uniform network overlay (the existing DoD backbone network is based on ATM), enforcement of Quality of Service (QoS) for applications requiring guaranteed network bandwidth or latency, and the ability to scale the network readily in speed or geography without costly re-design. Therefore, as the Navy's requirements for shipboard communications scale, the technology will be able to meet those needs.

VI. REFERENCES

[1] Abbe, B.S., M.J. Agan, and T.C. Jedrey, "ACTS Mobile Terminals," International Journal of Satellite Communications, Special Issue on ACTS, Volume 14, Issue 3, May/June 1996.

[2] Axford et al., "ACTS Mobile Terminal on USS Princeton (CG59)," Milcom97, Nov. 1997.

[3] D. Beering and D. M. O'Neill, "API's ARIES Project: Current status, future plans," The Leading Edge (Society of Exploration Geophysicists), pp.1351-1354, December, 1996

[4] M. Rupar and D. Beering, "A Ka-band Shipboard Satellite Terminal," Milcom99, Oct. 1999.

[5] Rupar, et al, "The Shipboard ACTS Ka-band Experiment," NRL Formal Report, (pending).

Fig. 1 The Entropy with Ka-band terminal, near Navy Pier, Lake Michigan

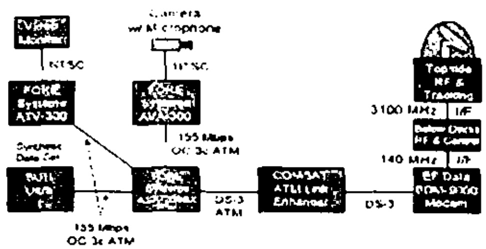

Fig. 2: Shipboard HDR Network Diagram, Entropy

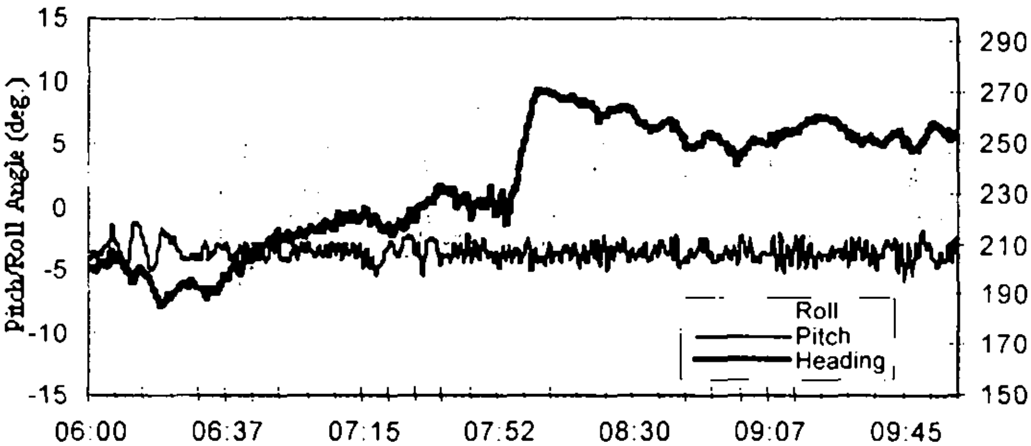

Fig. 3: Measured vessel motion for Entropy, October 22, 1998, run #38. A complete loss of track of the satellite occurred at 11:23:07 PM.

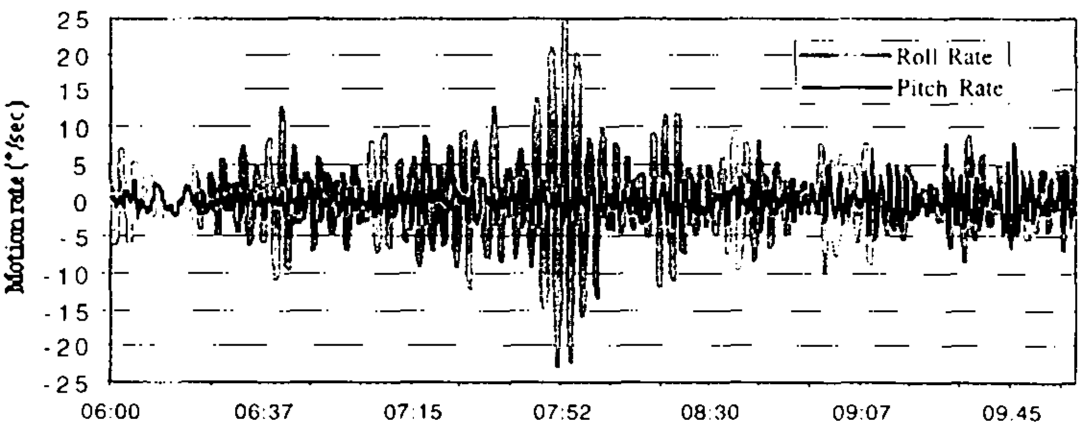

Fig. 4: Measured vessel pitch and roll rates for Entropy, run #38.

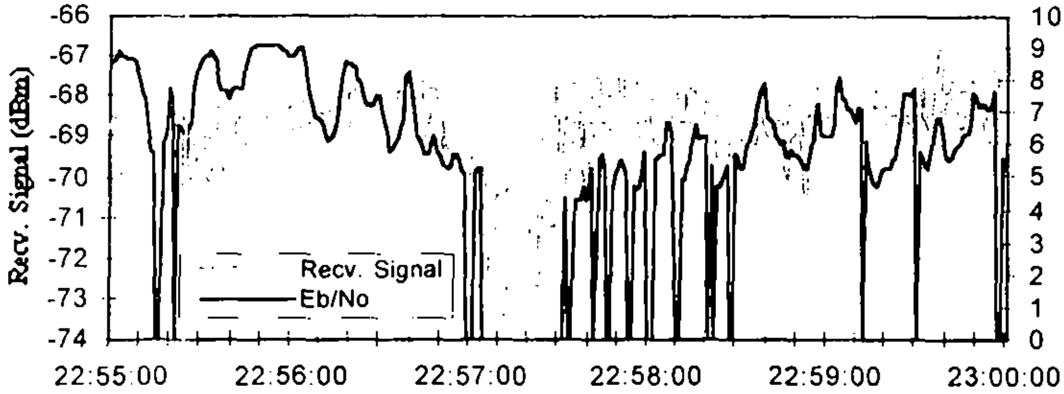

Fig. 5: Received Signal and Eb/No at theSDM-9000 Modem measured during a signal dropout in run #38.

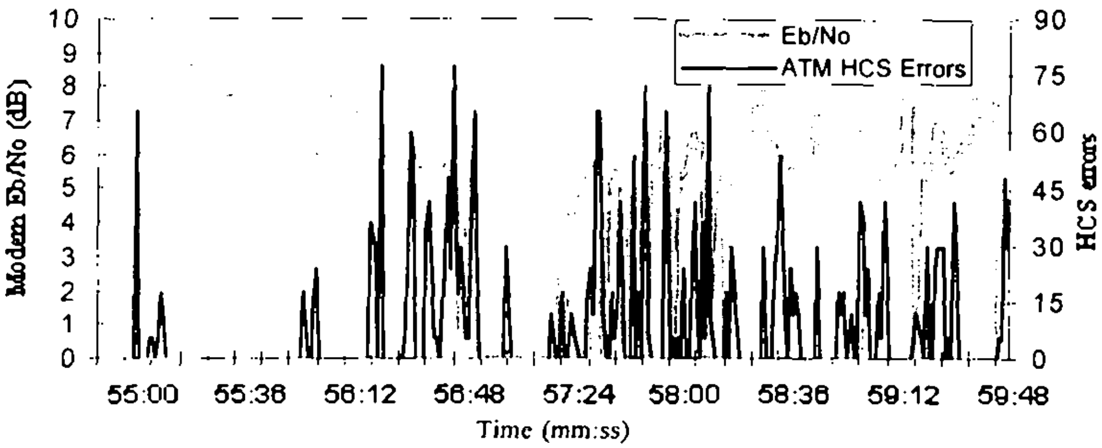

Fig. 6: Eb/No at the modem measurements along with simultaneous ATM header check sum (HCS) errors at the switch (?) on the Entropy, during the same signal dropout, run #38.

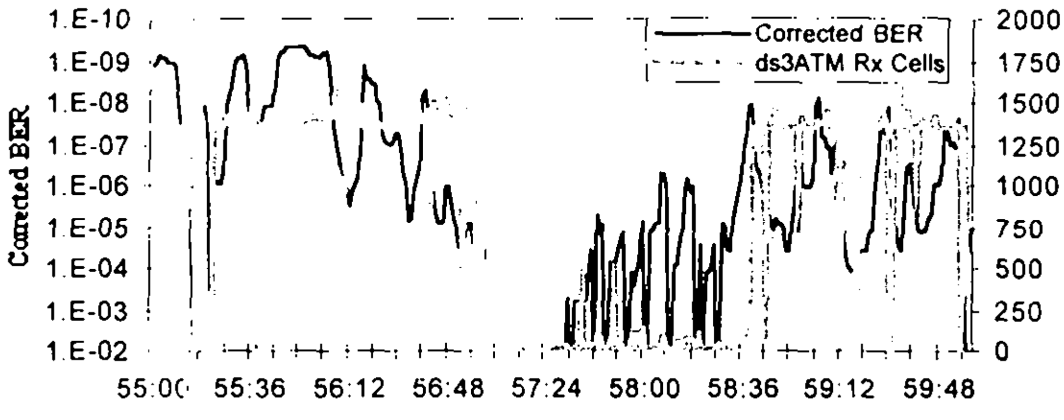

Fig. 7: Modem corrected bit error rate (BER) and received ATM cells at the Entropy, during the same signal dropout, run #38.

FileEnd

FileEnd

5th Ka-Band

PERFORMANCE OF ACTS AS A Ka BAND TEST BED

Richard J. Krawczyk
NASA-Glenn Research Center
Cleveland, Ohio 44135 USA
PH: 216.433.3539
e-mail: r.krawczyk@grc.nasa.gov

Frank Gargione
Analex Corporation
Brook Park, Ohio 44142 USA
PH: 609.883.4778
e-mail: gargion@ibm.net

Abstract

The Advanced Communication Technology Satellite (ACTS) Program was originally conceived as a two-year mission to demonstrate new Ka Band technologies and their potential applications via a geostationary communications test-bed. The excellent performance and versatility of the satellite subsystems has enabled system operation to be extended into a 7th year. The current and final phase of the mission now includes inclined orbit operation. In this phase, autonomous roll biasing coupled with periodic East/West maneuvers provide the fine pointing needed by the narrow (0.3 degree) spot beams to enable high-quality experiments and demonstrations. This paper reports on the performance of the various communications payload and spacecraft bus subsystems in terms of telemetry data and experience-based operational characteristics that have been observed and recorded over the life of the satellite.

The objective of this paper is to increase the confidence of the user and investor communities considering operation of Ka Band systems, which demand more complex designs incorporating on-board switching, small spot beams, fine pointing, rain fade compensation and other operational refinements to provide service directly to the end user. By documenting the stable performance of the ACTS systems, we hope to provide a factual basis to alleviate the concerns raised by the additional complexities demanded by operation at Ka Band.

Introduction

The Advanced Communications Technology Satellite (ACTS), conceived and designed in the 1980's but delayed by funding constraints during manufacture, implements features of great interest to those currently involved with upcoming Ka band satellite systems. These features include four extremely wideband medium power transponders, a multiple spot beam antenna system and on-board baseband processing and microwave switching systems.

Since launch in September 1993 these new technology items have operated without failure for over 52,000 hours. The Ka Band payload has additionally seen over 500 power cycle and thermal transients during 13 eclipse seasons, conditions not seen by commercial satellites equipped with high capacity batteries to maintain continuous operation.

The static switching and reconfiguration capabilities within the payload have enabled multiple simultaneous users, allowing more efficient experiment scheduling and flexibility.

The narrow, 0.3° spot beams produced by the 30/20 GHz multibeam antenna required more precise pointing by the satellite attitude control system. The pointing was achieved using an RF autotracking subsystem that has performed as intended.

Throughout the program various operational techniques were developed to improve specific areas of performance. The continued excellent health of the satellite bus and payload hardware challenged program management to extend useful operation with minimum impact to the fuel budget and little additional resources. Preparations were made for inclined orbit operation, exploiting the previously unused programmability of the attitude control system processor to maintain antenna pointing as satellite inclination increases with time after exhaustion of fuel for North/South stationkeeping maneuvers. ACTS has been operated in this inclined orbit mode since August 1998.

Satellite Components and Subsystems Performance

To assist the reader in better understanding the discussion to follow, a simplified block diagram of the ACTS payload is shown in Figure 1.

Low Noise Receivers

The low noise receivers at the input of the four Ka band transponders provided a 3.8 dB noise figure, yielding peak G/T values of 19.17 to 24.26 dB/°K for the various uplink spot beams. Six years of operation in space have shown no evidence of degradation of the High Electron Mobility Transistor low noise amplifiers or other receiver components based on links and margins currently achieved by the 0.6 to 3.4 meter terminals deployed throughout the ACTS system.

Transmitters

The four transmitters each include an IF to RF (3.5 to 20 GHz) upconverter followed by a 46 watt TWTA. A limiting amplifier in the upconverter maintains TWT input constant at the saturation point across the 19.2 to 20.1 GHz band. The TWTA was equipped with more instrumentation than is common on commercial satcom transmitters, where extra power for instrumentation would cause intolerable reduction in DC to RF efficiency, so that NASA could evaluate the long-term stability of the amplifiers and collect data to aid the commercial satellite industry. The ACTS TWTs have a long life M-type dispenser cathode and a dual-stage depressed collector and have accumulated over 180,000 tube hours on-orbit. Inspection of telemetry data from the TWTA instrumentation confirms our operational experience of extreme stability for these devices. As indicated in Table 1, comparing data taken in 1993 and 1999, the TWT parameters and the sensors themselves continue to exhibit excellent stability. The data was compared over a 24-hour period on days with same payload configuration and similar temperature profiles. TWTA 4 shows slightly more variation in helix current but still well below the 3.5 mA trip point implying many more years of life. There have been no spurious shutoffs or indications of high voltage problems. The Electronic Power Conditioner (EPC) and TWT internal design and assembly and high voltage encapsulation techniques continue to perform as intended after over 500 power/thermal cycles during eclipses.

Parameter	TWTA1 1993	TWTA1 1999	TWTA2 1993	TWTA2 1999	TWTA3 1993	TWTA3 1999	TWTA4 1993	TWTA4 1999	Units
Output Power	45.17 44.94	44.94	45.90 45.69	45.90 45.69	45.46 45.26	45.26 45.06	46.11	46.11 45.86	dBm
Cathode Current	48.15	48.15	48.18	48.18	48.42 48.18	48.42 48.18	48.65	48.65	mA
Anode Voltage	1.006 1.001	1.001 0.995	1.040	1.040 1.035	0.938	0.938 0.933	0.758	0.748 0.739	-kV
Helix Current	1.140	0.924 0.865	0.758 0.739	0.719 0.680	0.790 0.771	0.967 0.869	1.207 1.148	1.559 1.442	mA

Table 1 – TWTA Telemetry Diurnal Range (single value indicates no change over 24 hours, two values indicate max/min range)

Multibeam Antenna

The multiple spot beam antenna system (MBA), one of the key technologies for upcoming Ka Band systems, was characterized early in the program [1]. Biasing the satellite in pitch and roll allowed determination of beam centers and evaluation of various outside perturbations peculiar to the ACTS MBA design and materials. It was determined that diurnal thermal effects, as solar flux illuminates different parts of the MBA assembly, could be adequately compensated by routine daily operational procedures. Subreflector distortions which affect the autotrack uplink signal and thus degrade satellite attitude control are compensated by temporarily switching from autotrack to earth sensor pointing reference. Downlink beam center drift is compensated by biasing of the transmit reflector with the gimbal drive originally intended for seasonal adjustments.

The MBA hopping spot beams are electronically selected by ferrite switches in beam forming networks. To date 36 of the 48 beams have been used to enable experiments throughout the USA. No problems have been attributed to the beam forming networks although on very rare occasions it has been observed that not all selected beams "light up". This only occurs in conjunction with a post-eclipse turn-on of the control electronics and is corrected by memory reset and reload commands.

One of the hopping beams is actually a one-meter steerable beam reflector (SBA) which can be steered over the entire hemisphere visible from 100° West. The SBA has enabled Ka band experiment sites from Antarctica to the Arctic Circle even though its gain is over 6 dB lower than the main beams. Ground software developed to automatically generate and execute SBA pointing commands based on real-time reports of geographic position from mobile users has enabled unique experiments through ACTS with forward and return links tracking airborne and shipboard terminals.

Baseband Processor

The Baseband Processor (BBP) continues to provide bandwidth on-demand, enabling a full mesh, single hop TDMA network at rates from 64 kbps to T1 using Very Small Aperture Terminals (VSATs) equipped with 1.2 meter antennas. The largest network to date has been a total of 21 terminals spread over 12 spot beams, although the BBP architecture is designed accommodate a fleet of up to 40 terminals.

The BBP demodulates 27.5 and 110 Mbps uplink bursts, routes individual 64 kbps circuits, and regenerates downlink bursts at 110 Mbps with selective fade compensation for network connectivity via the hopping spot beams. Pre-launch reliability modeling of the resultant circuit complexity and high parts count identified the BBP as the overall driver of payload reliability. Although calculated reliability decreases as operating hours increase, the on-orbit philosophy has been to maximize power-on time to avoid the electrical and thermal stresses of unnecessary power cycling. Over 500 power cycles during eclipses have occurred and the primary side of the BBP accumulated over 41,000 hours before it was decided to switch to backup components. This was done primarily to investigate a rare downlink frame mis-acquisition now isolated to an occasional noise susceptibility in a primary component.

No memory or processing failure has been encountered in operation to date. The BBP architecture inhibits the effect of any potential SEU-induced bit errors, and therefore an occasional soft error of this type would be cleared by the error detection and correction if occurring within control memories or would contribute imperceptibly to Bit Error Rate (BER) if occurring in the data memories.

Microwave Switch Matrix

The ACTS Microwave Switch Matrix (MSM) implements another form of on-board switching applicable to multibeam communications satellites. It has a 4X4 crossbar switch architecture consisting of 16 GaAs FET switch amplifier modules with 100 ns switching speed and flat gain across the 3.0 to 4.0 GHz IF band. The MSM's digital control unit is implemented with CMOS ICs and is routinely programmed, via the command uplink, for the required uplink to downlink connectivity. This can be static or dynamic satellite switched connectivity, with 1 or 32 ms frames, using fixed or hopping spot beams. This capability has enabled a broad range of users, from mobile terminals and USATs in the static bent-pipe mode to 696 Mbps burst rate SS-TDMA for point-to multipoint full duplex interconnection of fiber networks [2]. No problems have been encountered with the control logic or the hybrid switch modules of the MSM.

Propagation Beacons

A significant effort in the promotion of Ka-band systems is providing adequate propagation data. For the last six years ACTS has provided a CONUS signal stable to within 1 dB from the 20.185 GHz telemetry beacon and the unmodulated 27.505 GHz uplink fade beacon. The second (20.195 GHz) telemetry beacon was activated in December 1998, without telemetry modulation, to provide a tracking reference for high data rate earth stations. The primary telemetry beacon has remained stable since launch even though it exhibits periodic variations now familiar to propagationists. These variations include a 0.4 dB shift during spacecraft ranging, pattern variations due to diurnal thermal gradients on the CONUS antenna feed tower and frequency shifts with bus voltage variations during eclipse entry/exit.

Attitude Control System Performance

The autotrack pointing function of the attitude control subsystem begins and ends with the MBA. The MBA feed system and autotrack receiver process the Cleveland uplink reference signal to provide the pitch and roll error signals to satisfy pointing requirements for the narrow spot beams. The autotrack receiver has demonstrated over 22 dB of dynamic range to accommodate severe rain fades. Tight pitch control, better than 0.01°, is maintained by a momentum wheel while roll and yaw are each controlled by a magnetic torquer. Yaw error is sensed by east-and west-facing sun sensors, providing approximately eight hours of yaw input data that also feeds into an estimator algorithm that provides pointing control input for the other 16 hours.

Figure 2 shows roll and yaw data over one 48-hour period in 1998, typical of satellite pointing stability since 1994. The previously mentioned MBA subreflector thermal distortion can introduce over 0.1° attitude error at certain times of the day, 1400 to 1900 GMT in the figure, if not compensated by switching to the less precise earth sensor (ESA) for its better average stability during these periods. This is a manual operation where satellite controllers monitor the attitude errors prior to ESA/autotrack transition to add small biases if needed to ensure smooth transitions.

An initial uncertainty in the operation of ACTS was the ability to maintain spot beam communications during the stationkeeping maneuvers needed to maintain the spacecraft in its assigned geostationary position. Experience has proved that antenna pointing and experiment operations could continue uninterrupted through these maneuvers since rate gyros and thrusters maintain adequate attitude stability.

Inclined Orbit Operation

The long term excellent performance of the satellite bus and communications payload has exceeded the fuel available for geostationary operation and north-south stationkeeping was terminated in July 1998. To continue using ACTS as a geosynchronous test bed while conserving the remaining fuel for deorbiting, NASA took advantage of the programmability of the attitude system processor (ASP) which made possible autonomous satellite roll control to maintain adequate pointing while orbit inclination increases by 0.8° per year.

New operations procedures now include periodic uploads to the ASP of diurnal tables for sinusoidal stepping of the momentum wheel pivot and roll biasing, additional sun position corrections for yaw sensing and daily sidereal clock correction. The pivot stepping maintains the momentum axis normal to the equatorial plane to minimize attitude perturbations and the roll biasing holds ESA close to autotrack.

Table 2 lists attitude control performance at various points in mission life. Figure 3 indicates typical attitude control performance one year after Figure 2, where the resulting inclination is 0.8°. The additional "noise" on the roll signal that was not present in Figure 2 is due to the continuous incremental stepping of the pivot. It can be seen that yaw and autotrack roll compare very well with pre-inclined performance.

Ka Band Command and Telemetry Links

The daily operation of ACTS is coordinated from the Master Ground Station (MGS) at NASA Glenn Research Center in Cleveland, Ohio, USA and executed via Ka band command and telemetry links. Experiment coordinators generate an experiment schedule that defines the configurations required of the communications payload. This is coupled with the required spacecraft operations to form a daily operations plan. Measured link margins from the MGS are:

18 dB for high rate payload commands
24 dB for low rate bus commands
14 dB for telemetry

Heavy rain has caused occasional telemetry dropouts, as expected for a single site, from momentary to up to one half hour or more, but this has been totally acceptable for ACTS operations, since the spacecraft autonomously maintains correct pointing.

Power and Thermal Subsystems

Other satellite bus subsystems are also essential to the continued performance of the communications payload. The two sources of raw DC power, the solar array and the battery, share a conservative design philosophy and have had no problems. Initial solar array capacity was over 1800 watts and is currently near 1500 watts. This still provides ample margin since combined payload and housekeeping loads are less than 1200 watts.

Battery weight constraints in the late 1980's, when the ACTS mission was designed, dictated 19 amp-hour batteries intended to support essential housekeeping loads during eclipse, not to maintain continuous payload/experiment operation. This limits depth of discharge to less than 39% providing greater than 25.5 volts on discharge and has made battery reconditioning unnecessary, thus avoiding any potential risks associated with it.

The thermal control subsystem consists of heat pipes, heaters, thermostats and passive coatings and materials to maintain adequate satellite temperatures. Telemetry data returned from sensors show on-orbit temperatures are generally within 5°C of pre-launch predictions and all within the design operating range of the components.

Conclusions

The Ka band microwave components and advanced concepts implemented by ACTS have operated over six years on-orbit with the additional stress of over 500 power/thermal cycles during eclipses with no failures or significant degradation. Multiple payload reconfigurations each day have enabled a multitude of technology demonstrations and experiments.

The overall capability of ACTS as a versatile communications test bed has allowed it to synergistically evolve with the terrestrial fiber technologies and the development of new terminals. Although the specific hardware implementations may be peculiar to ACTS, its demonstrated successful performance is a major milestone to bolster the acceptance of new Ka-band systems and services.

References

1. R. Acosta, "ACTS multibeam antenna analysis and on-orbit performance," in *2nd Ka-Band Utilization Conf.*, Florence, Italy, Sept. 1996.

2. R. Acosta, R. Bauer, R Krawczyk, R. Reinhart, M. Zernic, F. Gargione, "Advanced Communications Technology Satellite (ACTS): Four-Year System Performance," *IEEE J. Selected Areas in Comm.*, Vol. 17, No. 2, February 1999.

AXIS	SPECIFICATION REQUIREMENT	PRE-LAUNCH PREDICTION	TYPICAL PRE-INCLINE	INCLINED 2° PREDICTION
Pitch	0.025°	0.0213°	0.01°	0.0164°
Roll	0.025°	0.0235°	0.02°	0.0475°
Yaw	0.150°	0.144°	0.15°	0.217°

Table 2. Attitude Control Pointing Error (autotrack mode)

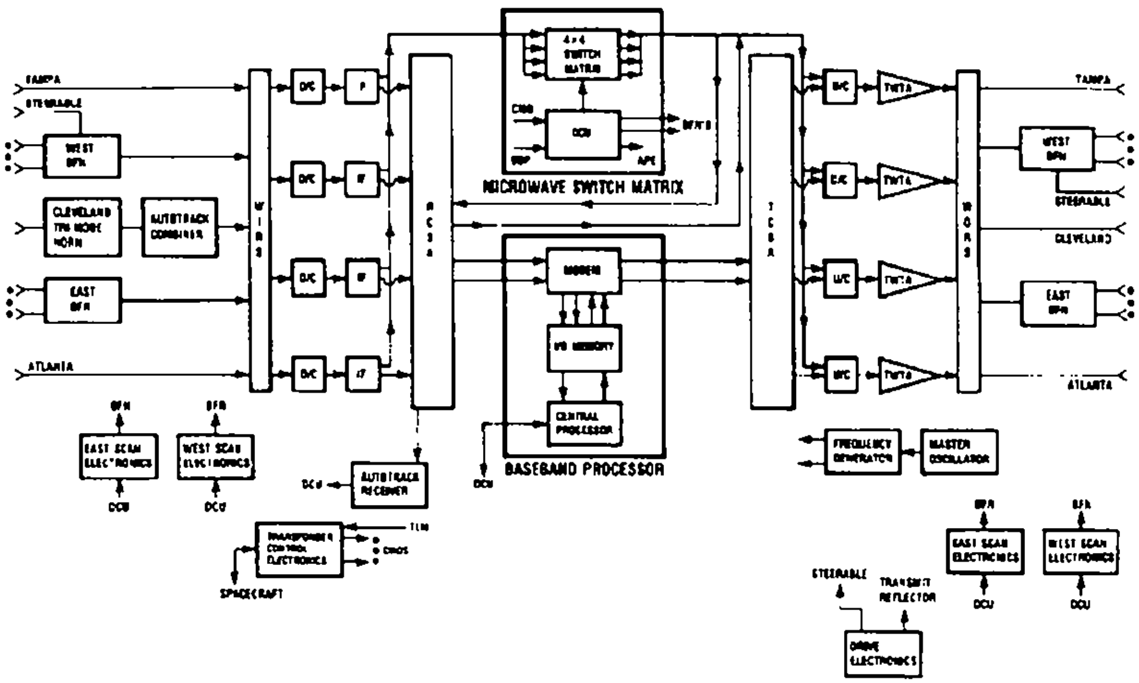

Figure 1 – ACTS Payload Block Diagram

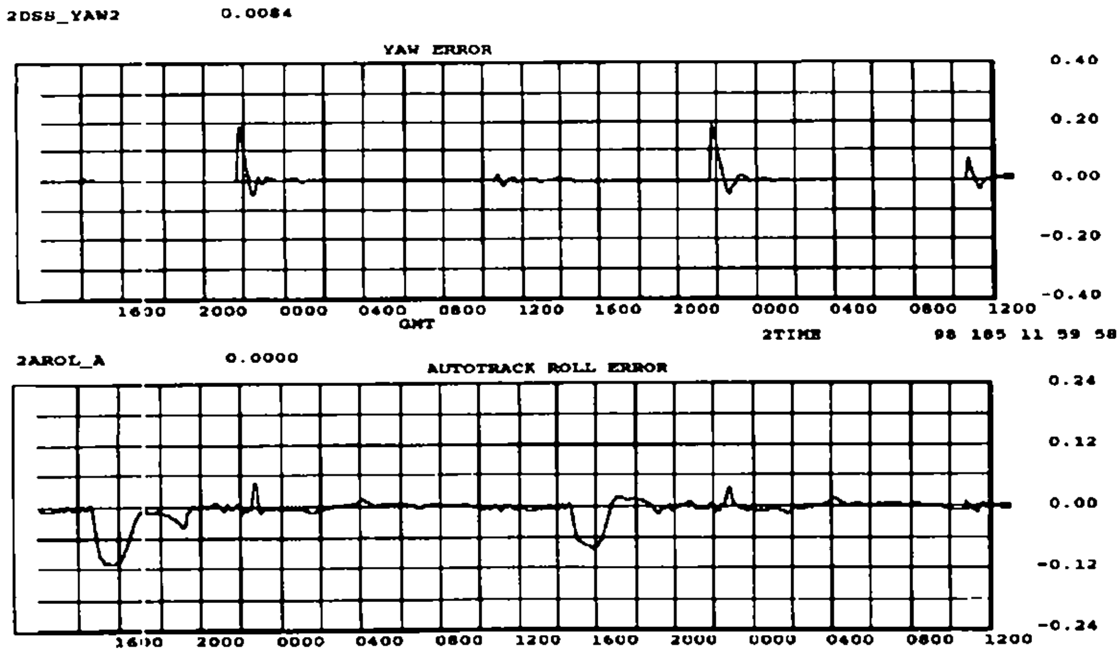

Figure 2. Attitude Control Performance (no inclined orbit)

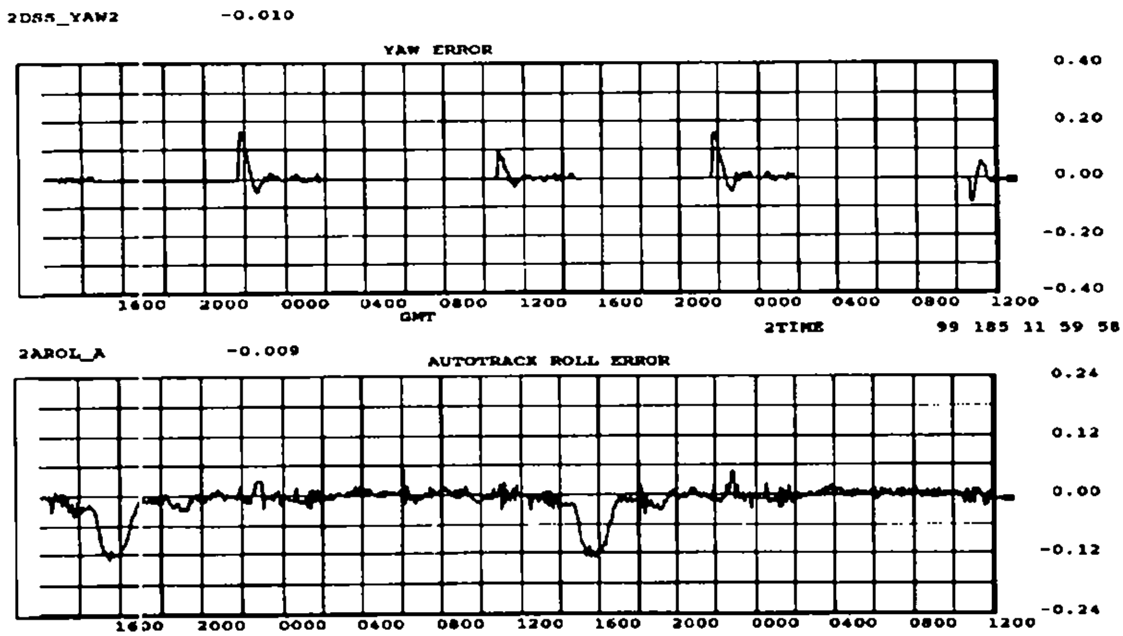

Figure 3. Attitude Control Performance (inclined 0.8°)